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Mass-transport deposits, olistostromes and soft-sediment deformation in modern and ancient continental margins, and associated natural hazards

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Mass-transport deposits (MTDs), olistostromes and related soft-sediment deformation structures represent significant components of the geological architecture of both modern and ancient continental margins, including active, passive and hybrid margin types (Dilek and Rowland, 1993; Stoker et al., 1998; Dilek and Robinson, 2003; Lamarche et al., 2008; Madon, 2010; Ratzov et al., 2010; Anma et al., 2011; Pini et al., 2012; Festa et al., 2013), and are commonly associated with earthquakes and tsunamis (e.g., Tappin et al., 2008). These tsunamic events adversely affected the human populations, engineering infrastructures and global economy, and inflicted severe and locally irrecoverable damages on the coastal ecosystems (e.g., Yamada et al., 2012 and references therein).

Improving our understanding of the mechanisms and processes of slope failure and MTD development, their spatial and temporal relationships with seismic events, and the dynamic equilibrium of active, passive and hybrid continental margins is one of the most urgent and challenging tasks faced by modern Earth science. To that end, a key approach to increase our scientific knowledge on these topics of both great scientific and societal importance is a comparative analysis of modern and ancient examples of MTDs, chaotic rock bodies and olistostromes (*sensu* Flores, 1955 or "sedimentary mélanges" *sensu* Bettelli and Panini, 1985; Festa et al., 2012), and the processes of their formation

Interdisciplinary investigations in the last 30 years of modern passive and active continental margins through 3D-seismic reflection, multibeam sonar and submersible studies (including drilling, coring and *in situ* sampling) and analogue modeling played a major role in our comprehension of the mode, nature and scale of the formation of modern submarine MTDs with respect to their causative events. On the other hand, on-land studies of exhumed, ancient MTDs (or olistostromes) have provided useful information on their internal structure and stratigraphy at scales (meters to hundreds of meter) that are commonly difficult to obtain through marine studies mainly because of poor acoustic transparency below the standard seismic resolution. Hence, studies of modern and ancient MTDs/olistostromes are highly complementary and essential.

Olistostromes represent, in fact, excellent fossil examples of modern submarine MTDs (see Pini et al., 2012), produced by different types of gravity-mass movements, such-as block slides, debris avalanches and debris flow, and hyperconcentrated flows (Lucente and Pini, 2008). Recent studies of some large-scale chaotic bodies exposed on land that originated by en-mass gravitational processes, including olistostromes and sedimentary mélanges (see, e.g., Alonso et al., 2006; Callot et al., 2008; Burg et al., 2008; Lucente and Pini, 2008; Camerlenghi and Pini, 2009; Festa et al., 2010, 2012; Remitti et al., 2011; Wakabayashi and Dilek, 2011; Codegone et al., 2012a, 2012b; Dilek et al., 2012; Pini et al., 2012), have shown that these fossil MTDs are comparable in size and style to some of the largest modern submarine landslides documented in the literature. Comparison of modern (offshore) and ancient (on-land) examples of MTDs is thus fundamental not only to better understand their formation, but also to develop more effective countermeasures to mitigate their tremendous humanitarian and economic impact.

This Special Issue has emanated from two successful scientific sessions on the occurrence of modern and ancient MTDs, olistostromes and mélange formation, and related natural hazards that we convened at the American Geophysical Union Fall Meeting in San Francisco, California, in December 2011, and at the International Association of Sedimentologists (IAS) meeting in Schladming (Austria), in September 2012. The papers in this Special Issue present the most up-to-date observations and interpretations from a series of case studies on MTDs, olistostromes and related soft-sediment deformation structures. The geographic distribution of these examples is shown in Fig. 1. The papers include field-based structural, sedimentological, geophysical, deep-ocean drilling, and submersible studies of different modern and ancient continental margins. We thank Marine Geology for relaxing their policy on not publishing papers on rocks outcropping on land, so that this Special Issue can examine the relationship between the terrestrial and marine examples.

We have organized the papers in this Special Issue in two sections on modern (offshore) and ancient (on-land) MTDs and different processes of their formation. The first part includes four papers documenting some modern examples of MTDs, their internal structures, processes and mechanisms of their emplacement, and their role in triggering tsunami. The second part includes five case studies of ancient, on-land examples of MTDs (or olistostromes), which are closely comparable in terms of size, mechanisms of formation, and spatial and temporal relationships with the local tectonics, to those described in the first part.

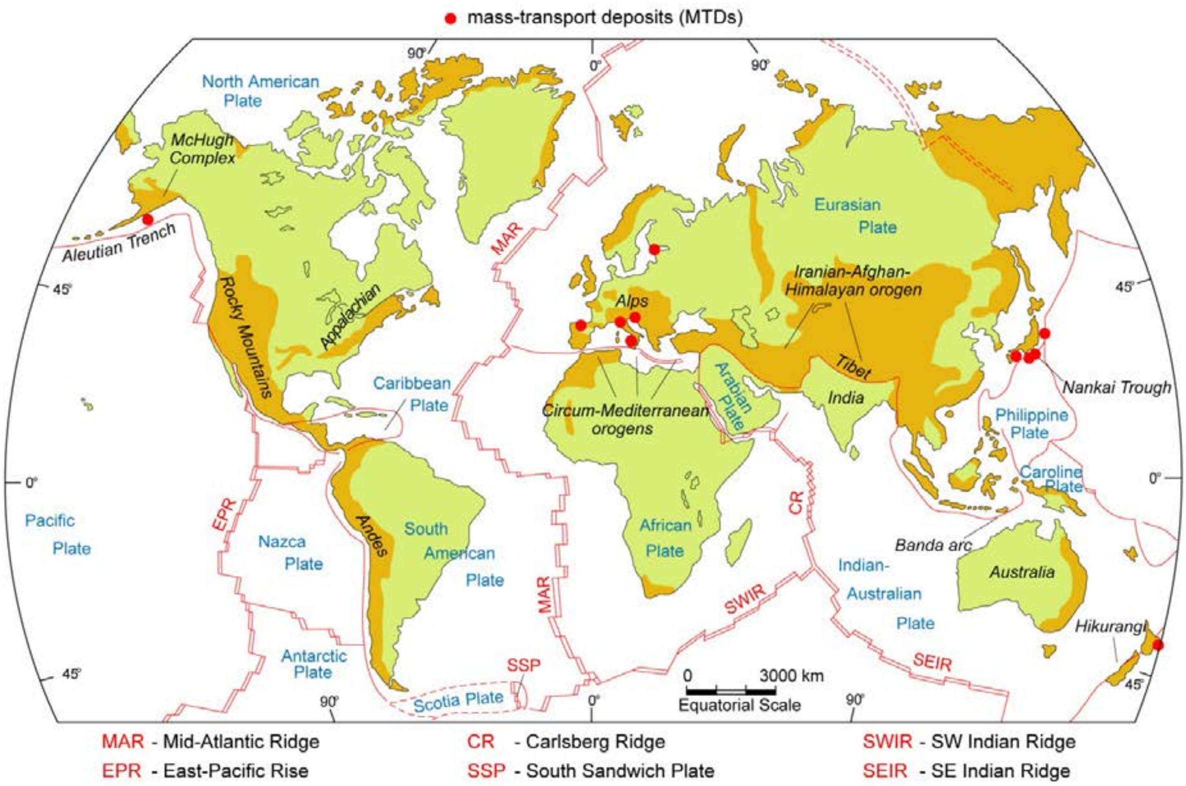

Figure 1 *- World map showing the lithospheric plates, their boundaries, and the case studies of mass-transport deposits (MTDs) covered by the papers in this Special Issue.*

Part I: Modern (offshore) examples of MTDs and associated natural hazards
The four papers in this section provide excellent examples of MTD studies in different tectonic settings, and show the important role played by tectonics in triggering modern MTDs and tsunami.

Alves et al. describe a submarine channel system and basal ramps of a Quaternary mass-transport deposit (MTD) in the Nankai accretionary wedge and document the role played by thrust faulting in its formation. They show that the geometrical character of the MTD contrasts with that commonly documented from frontally-emerged submarine landslides. Oblique basal ramps form significant boundaries between MTDs that developed channel systems, controlling the transport direction of the studied MTD. This direction deviates 30°- 45° from the general attitude of the fault scarps and ramps and the associated folds. The channel systems can erode the upper continental slope and carry significant volumes of sediments to distal parts of the accretionary wedge in periods of more intense thrust-wedge deformation with respect to those predicted by models.

Nowak et al. report the magnetic fabric analyses (i.e., anisotropy of magnetic susceptibility – AMS) of sub-units of MTDs in the same section of the Nankai accretionary wedge described by Alves et al. They provide new insight into the paleoccurent direction and depositional processes, showing that the magnetic fabric analyses are useful in identifying sediment disturbance and direction of movement at the time of emplacement. They show that sedimentary deposits that are unaffected by MTDs record episodic changes in paleocurrent direction and different types of sedimentological processes (i.e., slope gravity, viscous suspension, grain collision, etc.).

Rovere et al. describe the geomorphometry of a submarine mass-transport complex and its relationships with active faults in a rapidly uplifting margin in the Gioia Basin area facing the Costanea Ridge (NE Sicily, Italy). They document, through new high-resolution swath bathymetry and seismic data, the headwall areas of the frontally-confined Villafranca slide and its debris flow lobes, and the presence of seafloor fluid escapes (pockmarks) in the Acquarone Ridge. They show the rectilinear trend of the main headwall scarps exploiting the pre-existing normal faults during the episodes of accelerated uplift.

Kawamura et al. discuss and review some case studies of modern and historical submarine landslides in active continental margins that may have played a major role in tsunami generation. They argue that the triggering mechanism of these landslides appears to be related to the nature and location of the active faults and related seismic events, and to the properties of sediments prior to slope failure. They show that large tsunamigenic submarine landslides commonly occur on non-accretionary continental margins, and outline the possible implications of their results for the existing tsunami warning system in Japan.

Part II: Ancient (exhumed) examples of MTDs, olistostromes and soft-sediment deformation
The five papers in this section document different examples of basin-wide MTDs, involving the entire spectra of mass-transport processes (e.g., sliding, slumping, debris flow and avalanches) and various types of soft-sediment deformation structures extending over large regions (up to 9000 km^2).

Ogata et al. present an integrated outcrop-geophysical study of two comparable examples of MTDs, the exhumed Specchio unit in the Northern Apennines (Italy) and the Holocene Poverty unit in the Hikurangi margin (New Zealand). They show that the combination of micro- to meso-scale multidisciplinary analyses carried on continuous 3D outcrops (i.e. the Specchio unit) and acoustic imaging of the present-day continental margin sequences (i.e., the Poverty unit) provide new and significant information on submarine landslide processes and mechanisms. They highlight the fundamental role of shearing-related liquefaction as one of the main factors controlling slide mobility through the “lubrification” of the internal and basal friction forces. Understanding of these features is significant in improving the characterization of MTDs originated by potentially catastrophic, long run-out transport events and related tsunamis.

Yamamoto examines dewatering and soft-sediment deformation structures formed under the influence of slope instability in the late Miocene–Pliocene Miura-Boso accretionary prism and the Plio-Pleistocene trench-slope basin (Central Japan). He reports that pore fluid migration and an increase in pore fluid pressure were critical for slope instability, and in triggering failure within sediments close to the critical state. His findings demonstrate that the pore-fluid behavior associated with shear stress may play a significant role in slope failure patterns and their location.

Martin-Merino et al. report on the occurrence of large-scale mass-transport deposits formed in two wedge-top basins within the Varisican foreland (Cantabrian Zone, Spain). They document the composition, internal organization and lateral changes of the MTDs, as well as their frequency and significance in a tectonically active depositional setting. These MTDs were caused by the failure in shelf to slope environments and by several large-scale collapse events resulted from the growth of fault-propagation anticlines during the episodes of thrust faulting.

Ogata et al. report on the occurrence of basin-wide MTDs (i.e., carbonate "megabreccia" units) in the Friuli Basin (Italy-Slovenia boundary) produced by a catastrophic collapse of a shallow-water carbonate platform. These MTDs were subsequently re-deposited in an inner foredeep basin in front of the advancing Dinaric thrust front. The authors argue that the shape of this basin and its margins controlled the emplacement of the MTDs, which consist of bipartite slide masses with a lower coherent/cohesive blocky flow and an upper grain/turbulent flow.

Põldsaar and Ainsaar document numerous soft-sediment deformation occurrences, preserved within a meter-scale, deformed sandstone horizon in the nearshore Middle Ordovician deposits of the Baltoscandian Basin that extends over an area of about 9000 km^2 from NW Estonia to SE Sweden. They report that different types of soft-sediment deformation structures (e.g., flame structures, ball-and-pillow morphologies, meter-scale sedimentary dikes, autoclastic breccias, and other minor features) formed during a single seismic event (magnitude 7 or higher) that may have occurred during the Middle Ordovician (470 Ma ago) meteoritic bombardment period in the region.

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References
Alonso, J.L., Marcos, A., Suàrez, A., 2006. Structure and organization of the Porma mélange:progressive denudation of a submarine nappe toe by gravitational collapse. American Journal of Science 306, 32–65.

Alves, T.M., Strasser, M., Moore, G.F, 2014. Erosional features as indicators of thrust fault activity (Nankai Trough, Japan). Marine Geology (this volume), http://dx.doi.org/10.1016/j.margeo.2013.07.011.

Anma, R., Ogawa, Y., Moore, G., Kawamura, K., Sasaki, T., Kawakami, S., Dilek, Y., Michiguchi, Y., Endo, R., Akaiwa, S., and YK99-09, YK00-08, YK05-08 & YK06-02 Shipboard Science Parties, 2011. Structural profile and development of accretionary complex in the Nankai trough, off Kii peninsula, Southwest Japan: results of submersible studies. In: Ogawa, Y., Anma, R. & Dilek, Y. (Eds.), *Accretionary Prisms and Convergent Margin Tectonics in the Northwest Pacific Basin*, Springer Science, Dordrecht, The Netherlands, 169-196, DOI: 10.1007/978-90-481-8885-7_8.

Bettelli, G., Panini, F., 1985, Il mélange sedimentario della Val Tiepido (Appennino modenese). Atti della Società dei Naturalisti e Matematici di Modena, v. 115, 91–106.

Burg, J.P., Bernoulli, D., Smitt, J., Dolati, A., Bahroudi, A., 2008. A giant catastrophic mud-and-debris flow in the Miocene Makran. Terra Nova 20, 188–193.

Callot P., Sempere T., Odonne F., Robert E., 2008. Giant submarine collapse of a carbonate platform at the Turonian-Coniacian transition: The Ayabacas Formation, southern Peru. Basin Research 20, 333–357.

Camerlenghi, A., Pini, G.A., 2009. Mud volcanoes, olistostromes and Argille scagliose in the Mediterranean region. Sedimentology 56, 319-365.

Codegone, G., Festa, A., Dilek Y., 2012a. Formation of Taconic Mélanges and Broken Formations in the Hamburg Klippe, Central Appalachian Orogenic Belt, Eastern Pennsylvania. Tectonophysics, v. 568-569, 215-229. Doi: 10.1016/j.tecto.2012.03.017

Codegone, G., Festa, A., Dilek, Y., and Pini, G.A., 2012b, Small-scale polygenetic mélanges in the Ligurian accretionary complex, Northern Apennines, Italy, and the role of shale diapirism in superposed mélange evolution in orogenic belts: Tectonophysics, v. 568-569, 170-184, doi: 10.1016/j.tecto.2012.02.003.

Dilek, Y. Robinson, P.T., 2003. Ophiolites in Earth History: Introduction. In, Ophiolites in Earth History, Geological Society of London Special Publication 218, 1-8.

Dilek, Y., Rowland, J.C., 1993. Evolution of a conjugate passive margin pair in Mesozoic southern Turkey. Tectonics 12, 954-970. doi: 10.1029/93TC01060.

Dilek Y., Festa A., Ogawa Y., Pini G.A. 2012. Chaos and Geodynamics: Mélanges, Mélange-forming Processes and Their Significance in the Geological Record. Tectonophysics, v. 568-569, 1-6. DOI: 10.1016/j.tecto.2012.08.002

Festa, A., Dilek, Y., Pini, G.A., Codegone, G., Ogata, K., 2012. Mechanisms and processes of stratal disruption and mixing in the development of mélanges and broken formations: Redefining and classifying mélanges. Tectonophysics 568-569, 7-24, doi: 10.1016/j.tecto.2012.05.021.

Festa, A., Pini, G.A., Dilek, Y., Codegone, G., 2010a. Mélanges and mélange-forming processes: a historical overview and new concepts, in: Dilek, Y. (Ed.), Alpine Concept in Geology. International Geology Review 52 (10-12), 1040-1105, doi: 10.1080/00206810903557704.

Festa, A., Dilek, Y., Codegone, G., Cavagna, S., Pini, G.A., 2013. Structural anatomy of the Ligurian accretionary wedge (Monferrato, NW Italy), and evolution of superposed mélanges. The Geological Society of America Bulletin 125, 1580-1598, doi: 10.1130/B30847.1.

Flores, G., 1955, Les résultats des études pour les recherches pétroliféres en Sicile: Discussion, *in* Proceedings of the 4th World Petroleum Congress: Rome, Casa Editrice Carlo Colombo, Section 1/A/2, p. 121–122.

Kawamura, K., Laberg, J.S., Kanamatsu, T., 2014. Potential tsunamigenic submarine landslides in active margins, Marine Geology (this volume), http://dx.doi.org/10.1016/j.margeo.2014.03.007

Lamarche, G., Joanne, C., Collot, J.-Y., 2008. Successive, large mass-transport deposits in the south Kermadec fore-arc basin, New Zealand: The Matakaoa Submarine Instability Complex. Geochemistry Geophysics Geosystems (G-Cubed) 9, DOI: 10.1029/2007GC001843.

Lucente, C.C., Pini, G.A., 2008. Basin-wide mass-wasting complexes as markers of the Oligo-Miocene foredeep-accretionary wedge evolution in the Northern Apennines, Italy. Basin Research 20, 49-71.

Madon, M., 2010. Submarine mass-transport deposits in the Semantan Formation (Middle-Upper Triassic), central Peninsular Malaysia. Bulletin of the Geological Society of Malaysia 56, 15 - 26, doi: 10.7186/bgsm2010003.

Martín-Merino, G., Fernandez, L.P., Colmenero, J.R., Bahamonde, J.R. 2014. Mass-transport deposits in a Variscan wedge-top foreland basin (Pisuerga area, Cantabrian Zone, NW Spain), Marine Geology (this volume), http://dx.doi.org/10.1016/j.margeo.2014.01.012

Novak B., Housen, B., Kitamura, Y., Kanamatsu, T., Kawamura, K., 2014. Magnetic fabric analyses as a method for determining sediment transport and deposition in deep-sea sediments. Marine Geology (this volume), http://dx.doi.org/10.1016/j.margeo.2013.12.001

Ogata, K., Mountjoy, J.J., Pini, G.A., Festa, A., Tinterri, R., 2014. Shear zone liquefaction in mass transport deposit emplacement: A multi-scale integration of seismic reflection and outcrop data. Marine Geology (this volume), http://dx.doi.org/10.1016/j.margeo.2014.05.001

Ogata, K., Pogačnik, Ž, Pini, G.A., Tunis, G., Festa, A., Camerlenghi, A., Rebesco, M., 2014. The carbonate mass transport deposits of the Paleogene Friuli Basin (Italy/Slovenia): internal anatomy and inferred genetic processes. Marine Geology (this volume).

Ogata, K., Tinterri, R., Pini, G.A., and Mutti, E., 2012, Mass transport-related stratal disruption within sedimentary mélanges: Examples from the northern Apennines (Italy) and south-central Pyrenees (Spain): Tectonophysics, v. 568-569, 185–199.

Pini, G.A., Ogata, K., Camerlenghi, A., Festa, A., Lucente, C.C., Codegone, G., 2012. Sedimentary mélanges and fossil mass-transport complexes: a key for better understanding submarine mass movements?, in: Yamada, Y., et al. (Eds.), Submarine mass movements and their consequences: Advances in natural and technological hazards research, 31. Springer Science+Business Media B.V., pp. 585–594.

Põldsaar, K., Ainsaar, L., 2014. Extensive soft-sediment deformation structures in the early Darriwilian (Middle Ordovician) shallow marine siliciclastic sediments. Marine Geology (this volume), http://dx.doi.org/10.1016/j.margeo.2013.08.012.

Ratzov, G., Collot, J.-Y., Sosson, M., Migeon, S., 2010. Mass-transport deposits in the northern Ecuador subduction trench: Result of frontal erosion over multiple seismic cycles. Earth and Planetary Science Letters, doi:10.1016/j.epsl.2010.04.048.

Remitti, F., Vannucchi, P., Bettelli, G., Fantoni, L., Panini, F., Vescovi, P., 2011. Tectonic and sedimentary evolution of the frontal part of fan ancient subduction complex at the transition from accretion to erosion: the case of the Ligurian wedge of the northern Apennines, Italy. Geological Society of America Bulletin 123, 51-70.

Rovere, M., Gamberi, F., Mercorella, A., Leidi, E., 2014. Geomorphometry of a submarine mass-transport complex and relationships with active faults in a rapidly uplifting margin (Gioia Basin, NE Sicily margin). Marine Geology (this volume), http://dx.doi.org/10.1016/j.margeo.2013.06.003.

Stoker, M.S., Evans, D., Cramps, A. (Eds.), Geological Processes on continental margins: Sedimentation, mass-wasting and stability. Geological Society of London Speciaal Publication 129, 355 pp.

Tappin, D.R., Watts, P., Grilli, S.T., 2008. The Papua New Guinea tsunami of 17 July 1998: anatomy of a catastrophic event. Natural Hazards and Earth System Sciences 8, 243–266 (www.nat-hazards-earth-syst-sci.net/8/243/2008/).

Wakabayashi, J., Dilek, Y., 2011. Introduction: Characteristics and tectonic settings of mélanges, and their significance for societal and engineering problems. In: Wakabayashi, J. and Dilek, Y. (Eds.), Melanges: Processes of formation and societal significance, Geological Society of America Special Paper 480, p. v-x, doi: 10.1130/2011.2480(00).

Yamada, Y., Oshima, T., Matsuoka, T., 2012. Slope failure in analogue models of accretionary wedges, in: Yamada, Y., et al. (Eds.), Submarine mass movements and their consequences: Advances in natural and technological hazards research, 31. Springer Science+Business Media B.V., pp. 343–353.

Yamamoto, Y., 2014. Dewatering structure and soft-sediment deformation controlled by slope instability: examples from the late Miocene to Pliocene Miura–Boso accretionary prism and trench-slope basin, central Japan, Marine Geology (this volume), doi: 10.1016/j.margeo.2014.05.016